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AU9540638

(12) PATENT ABRIDGMENT (11) Document No. AU-B-40638/95
(19) AUSTRALIAN PATENT OFFICE (10) Acceptance No. 672166

(Australian Petty Patent)

(54) Title
METHOD AND APPARATUS FOR PERFORMING SELECTIVE SIGNAL AVERAGING

International Patent Classification(s)
(51)[6] G01M 013/02 G01H 017/00

(21) Application No. 40638/95 (22) Application Date 22.12.95

(30) Priority Data

(31) Number (32) Date (33) Country
PN0234 22.12.94 AU AUSTRALIA

(43) Publication Date 19.09.96

(45) Publication Date of Granted Application 19.09.96

(71) Applicant(s)
COMMONWEALTH OF AUSTRALIA

(72) Inventor(s)
DAVID FORRESTER

(74) Attorney or Agent
DAVIES COLLISON CAVE, 1 Little Collins Street, MELBOURNE VIC 3000

(56) Prior Art Documents
AU 71926/87 G01M 13/00
AU 499720 11706/76 G01M 13/04
AU 476958 70368/74 G01M 13/00

(57) Claim

1. A method for estimating the contribution, due to individual ones of a plurality of planet gears in an epicyclic gearbox having a ring gear, in a vibration signal generated by sensing vibration of a ring gear of the gearbox at a location on the ring gear during operation of the gearbox, comprising filtering the vibration signal by application of filter functions which models the time variation of the vibration signal at said location which would occur if only respective ones of said planet gear were present, said functions, for individual planet gear and, being of form:

$$\beta_p(t) = \left(\alpha\left(1 + \cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)\right)^n$$

where f_c is the frequency of rotation of the planet carrier;

α and n are constants;

P is the number of planet gears; and

t is time,

or said filter function being of form

$$\beta_p(\phi) = \left(\alpha\left(1 + \cos\left(\phi - \frac{p2\pi}{P}\right)\right)\right)^n$$

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where ϕ is the angular position of the planet carrier;

P identifies the individual planet gear;

a and n are constants; and

P is the number of planet gears;

wherein the filter functions β_p satisfy the following:

(a) $$\sum_{p=0}^{P-1} \beta_p(\phi) = \text{constant for all } \phi \text{ and,}$$

(b) $$\sum_{k=0}^{N-1} \beta_p\left(\phi + k2\pi \frac{N_p}{N_r}\right) = \text{constant for all } \phi$$

where ϕ is the angular position of the planet carrier;

N_p is the number of teeth on the planet gears;

N_r is the number of teeth on the ring gears; and

N is the number of rotations of the planet gear over which the signal averaging is performed; and

said constant n is in the range 0 to P−1; and

the filtered signal is averaged to produce measures of said contributions.

672 . 66 Regulation 3.2

AUSTRALIA

Patents Act 1990

PETTY PATENT SPECIFICATION

(ORIGINAL)

Name of Applicant: **Commonwealth of Australia, A.C.N. , of 506 Lorimer Street, Fishermans Bend, Victoria 3207, Australia**

Actual Inventor: **David Forrester**

Address for Service: **DAVIES COLLISON CAVE, Patent Attorneys, of 1 Little Collins Street, Melbourne, Victoria 3000, Australia**

Invention Title: **Method and Apparatus for Performing Selective Signal Averaging**

Details of Associated Provisional Application No. PN223[illegible]

The following statement is a full description of this invention, including the best method of performing it known to us:

This invention relates to a method of performing selective signal averaging of vibration data from epicyclic gearboxes. The method provides separate signal averages for the individual planets based on an estimate of each planet's contribution to the total vibration signal.

Signal averaging has proved a useful vibration analysis tool for detecting faults in gears. However, there has been a problem in applying the technique to epicyclic gearboxes. An epicyclic gearbox has a number of planet gears which all mesh with a sun gear and a ring gear, the planet gears being mounted for rotation on a carrier which itself rotates about the sun gear. The problems encountered when attempting to perform a signal average for components within an epicyclic gearbox are twofold. Firstly, there are multiple tooth contacts, with each planet gears being simultaneously in mesh with both the sun and ring gear, and secondly, the axes of the planet gears move with respect to both the sun and ring gears.

An earlier method of performing selective signal averaging on epicyclic gearboxes is described in ARL [1,2] which was claimed to be successful in detecting faults on individual planet gears. However, this method is somewhat tedious to implement, requires a relatively long time to perform even a small number of averages and requires selective chopping up of the time signal which introduces discontinuities in the signal average.

According to the present invention there is provided a method for estimating the contribution, due to one of a plurality of planet gears in an epicyclic gearbox having a ring gear, in a vibration signal generated by sensing vibration of a ring gear of the gearbox during operation of the gearbox, comprising filtering the vibration signal by application of a filter function which models the time variation of the vibration signal at said location which would occur if only said one planet gear were present.

The invention also provides a method for extracting a signal representing average vibration of one planet gear among a plurality of planet gears of an epicyclic gearbox.

In this method, a filtered signal for the one planet gear is averaged in such a way that the mean effect of the filter function is substantially constant, or at least be determinible and comparitable, over the complete revolution of the said one planet.

The invention also provides apparatus for estimating the contribution, due to one of a plurality of planet gears in an epicyclic gearbox having a ring gear, in a vibration signal generated by sensing vibration of a ring gear of the gearbox during operation of the gearbox, comprising means for filtering the vibration signal by application of a filter function which models the time variation of the vibration signal at said location which would occur if only said one planet gear were present.

The invention also provides apparatus for estimating the contribution, due to individual ones of a plurality of planet gears in an epicyclic gearbox, in a vibration signal generated by sensing gearbox vibration at a location on the ring gear of the gearbox during operation of the gearbox, comprising means for filtering the vibration signal by application of a filter function which models the time variation of the vibration signal at said location which would occur if only respective ones of said planet gear were present.

The filter function may be of form:

$$\beta(t) = [\alpha(1 + \cos 2\pi f_c(t - \theta))]^n$$

where f_c is the frequency of rotation of the planet carrier,

α and n are constants,

t is time; and

θ is the angular distance between the planet and the transducer at time $t=0$.

The constant α may be selected as required, such as for computational convenience, for example a value of 0.5 may be suitable. The constant n may be in the range 0 to P-1, such as P-1.

The filtered signal $v(t) = x(t)\,\beta(t)$ may be averaged to produce a measure of said contribution.

The invention also provides a method for estimating the contribution, due to individual ones of a plurality of planet gears in an epicyclic gearbox having a ring gear, in a vibration signal generated by sensing vibration of a ring gear of the gearbox during operation of the gearbox, comprising filtering the vibration signal by application of a filter function which models the time variation of the vibration signal at said location which would occur if only respective ones of said planet gear were present.

The filter function for individual planet gear P may be of form:

$$\beta_p(t) = \left(a\left(1 + \cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)\right)^n$$

where f_c is the frequency of rotation of the planet carrier;

a and n are constants;

P is the number of planet gears; and

t is time.

or

$$\beta_p(\phi) = \left(a\left(1 + \cos\left(\phi - \frac{p2\pi}{P}\right)\right)\right)^n$$

where ϕ is the angular position of the planet carrier;

P identifies the individual planet gear;

a and n are constants;

P is the number of planet gears.

The constant a may be selected as required, such as for computational convenience, for example a value of 0.5 may be suitable.

The filtered signals $v_p(t) = x(t)\ \beta_p(t)$ is averaged to produce measures of said contributions.

Usually, the filter functions β_p should satisfy at least one of the following, and preferably both:

$$(a)\qquad \sum_{p=0}^{P-1} \beta_p(\phi) = \text{constant for all } \phi \text{ and,}$$

$$(b)\qquad \sum_{k=0}^{N-1} \beta_p\left(\phi + k2\pi \frac{N_p}{N_r}\right) = \text{constant for all } \phi$$

where ϕ is the angular position of the planet carrier;

N_p is the number of teeth on the planet gears;

N_r is the number of teeth on the ring gears; and

N is the number of rotations of the planet gear over which the signal averaging is performed.

Generally, the above described methods and apparatuses according to the invention may be further applied in accordance with the invention to methods and apparatus for determining whether there is a fault in an epicyclic gearbox, by determining whether the derived component or components of the vibration signal due to a selected one or ones of the planetary gears are such as to be indicative of a fault. In particular, the aforementioned average signals may be compared with each other or with external references for this purpose.

In another aspect, averages for each of a plurality of planet gears are combined, such as by summing and dividing by the number of gears, and compared with an average for the vibration signal itself, to ascertain the extent to which information in the vibration signal has been utilised in practising the method of the invention. In particular, if the averages are the same, it may be taken that no information loss has occurred.

The ring gear vibration may be sensed by positioning the sensor on the ring gear, such as on or near the outside of this ring gear.

Preferably, the summation of the windows used for each planet, $w(t)$ as hereinafter defined, is constant for all time t.

Preferably too, the modulation effect introduced by the use of the window must cancel out in the final signal average, or be determinate and reversible.

The invention is further described by way of example only with reference to the accompanying drawings in which:

Figures (1a) and (1b) are diagrams of an epicyclic gearbox;

Figure 2 is a schematic diagram of apparatus for practising the method of the invention;

Figure 3 is a graph showing results obtained from demodulations of a vibration signal;

Figure 4 shows graphically the results of tests performed using the method of the invention and a prior art method;

Figure 5 shows results obtained by performing narrow band envelope enhancement on separated averages using the method of the invention and two other methods; and

Figure 6 comprises graphs illustrating the performance of the method of the invention as compared with a prior art method.

Epicyclic gearboxes are typically used in applications requiring a large reduction in speed (greater than three to one) at high loads, such as the final reduction in the main rotor gearbox of a helicopter. As shown in Figures 1(a) and 1(b), a typical epicyclic reduction gearbox 10 has three or more planet gears 12 each meshing with a sun gear 14 and a coaxially surrounding ring gear 16. Drive is provided via the sun gear, the ring gear is stationary and the planet gears are connected to a carrier 18 for rotation about fixed axes on the carrier. The carrier 18 rotates in relation to both the sun gear and ring gear. The planet carrier provides the output of the epicyclic gear train.

Where f_c, f_p and f_s are the rotational frequencies of the planet carrier, planet and sun gear respectively, (as marked in Fig. 1a) and there are N_r, N_p and N_s teeth on the ring, planet and sun gears respectively, the meshing frequency of the epicyclic, f_m, is given by:

$$f_m = N_r f_c = N_p(f_p + f_c) = N_s(f_s - f_c) \qquad (1b)$$

The relative frequencies, $f_p + f_c$ (Fig. 1b) of each planet gear to the carrier and $f_s - f_c$ (Fig. 1b) of the sun gear to the carrier gear are:

$$f_p + f_c = f_m/N_p = f_c\,(N_r/N_p) \tag{2}$$

$$f_s - f_c = f_m/N_s = f_c(N_r/N_s) \tag{3}$$

In practice, the gears will produce not only vibration at the tooth meshing frequency, but also at its harmonics.

Where it is desired to monitor the vibration of an epicyclic gear train a transducer 20 may be mounted on the outside of the ring gear. This gives rise to planet pass modulation due to the relative motion of the planet gears to the transducer location

As each planet approaches the location of the transducer 20, an increase in the amplitude of the vibration will be seen, reaching a peak when the planet is adjacent to the transducer then receding as the planet passes and moves away from the transducer. For an epicyclic gear train with P planets, this will occur P times per revolution of the planet carrier, resulting in an apparent amplitude modulation of the signal at frequency Pf_c.

Although the meshing frequency of all planets will be the same, it is likely that there will be a difference in phase of the vibration from each planet. If the planets are evenly spaced around the planet carrier, then the separation between planets will be N_r/P teeth. This results in a phase difference between the meshing frequencies of successive planets of $2\pi(N_r/P)$ radians. Unless the value N_r/P is an integer, the meshing frequencies will appear to differ by $(2\pi(N_r/P) \bmod 2\pi)$, where the function "mod" indicates the remainder after division.

The expected vibration signal from a transducer mounted on the ring gear of an epicyclic gear train, including planet pass modulation, phase differences and M harmonics of the planet meshing frequency, can be expressed as:

$$x(t) = \sum_{p=0}^{P-1} \alpha_p(t)\left[\sum_{m=1}^{M} A_{pm}\cos\left(2\pi m N_p(f_p+f_c)t + \frac{pN_r}{P} + \theta_0\right)\right] \tag{4}$$

where: $\alpha_p(t)$ is the amplitude modulation due to planet number p,

A_{pm} is the actual amplitude of harmonic m on planet p,

$(f_p + f_c)$ is relative rotation of planet gears,

N_p is the number of teeth on the planet gear,

N_r is the number of teeth on the ring gear,

θ_0 is the starting phase of planet 0.

The amplitude modulation function $\alpha_p(t)$ due to the planet pass would be expected to be symmetrical about the point at which the planet passes closest to the transducer, with the amplitude approaching zero when the planet is farthermost from the transducer. It is reasonable to assume that this function has the form (where planet 0 is assumed to be adjacent to the transducer at time t = 0):

$$\alpha_p(t) = \left(1 + \cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)^n \tag{5}$$

In this embodiment of the invention the signal x(t) is selectively divided between appropriate planets to provide an estimate of the contribution from each planet. This is done by making an estimate of the relative contributions of each planet mesh to the overall signal at any time t.

The function $\alpha_p(t)$, in equation (5) above, is an estimate for the amplitude modulation function as planet p moved around the ring gear. By multiplying the vibration signal by a function $\beta_p(t)$ similar to $\alpha_p(t)$,

$$\beta_p(t) = \left(1 + \cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)^n \tag{6}$$

or, more generally

$$\beta_p(t) = \left(\alpha\left(1 + \cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)\right)^n \qquad (6a)$$

signal due to planet p is reinforced, and signal due to other planets is attenuated. The estimate of the vibration signal extracted vp(t) for a single planet p is:

$$v_p(t) = x(t)\beta_p(t) \qquad (7)$$

The following two conditions should normally be met to ensure that the signal averages extracted using this method are valid:

(a) the summation of the windows used for each planet, $w(t)$ in equation (8) below, is constant for all time t and,

(b) the modulation effect introduced by the use of the window must cancel out in the final signal average, or be determinate and reversible.

Meeting condition (a) ensures that the sum of the individual planet averages is proportional to the sum of the total vibration (no loss of data). It is shown below that this condition is easily met if the order of the window is less than the number of planet gears.

Condition (b) ensures that no artificial distortion is introduced by the method. To meet this condition, the number of averages performed should be such that the applied window is repeated an exact integer number of times in the total period used for averaging. This will mean that every tooth will have had exactly the same accumulated window conditions applied over the total time of averaging.

In order to ensure that no loss of signal occurs, the proportion of the signal assigned to each planet must be such that the sum of the planet gear signals be proportional to the original signal. To achieve this the sum of the windows, $w(t)$, at any time t must be equal to a constant. The sum of the windows is:

$$w(t)=\sum_{p=0}^{P-1}\beta_p(t) = \sum_{p=0}^{P-1}\left(1+\cos\left(2\pi f_c t-\frac{p2\pi}{P}\right)\right)^n \tag{8}$$

Expanding:

$$\left(1+\cos\left(2\pi f_c t-\frac{p2\pi}{P}\right)\right)^n = 1+\sum_{j=1}^{n} c_j\cos^j\left(2\pi f_c t-\frac{p2\pi}{P}\right) \tag{9}$$

where cj are coefficients of expansion and

$$\cos^j\left(2\pi f_c t-\frac{p2\pi}{P}\right)=A+\sum_{k=1}^{j}\alpha_k\cos\left(k\left(2\pi f_c t-\frac{p2\pi}{P}\right)\right) \tag{10}$$

where A is constant and α_k are coefficients of expansion.

Applying (9) and (10) to equation (8) gives:

$$\begin{aligned} w(t) &= P+\sum_{p=0}^{P-1}\sum_{j=1}^{n}c_jA+\sum_{p=0}^{P-1}\sum_{j=1}^{n}\sum_{k=1}^{j}c_j\alpha_k\left[\cos(k2\pi f_c t)\cos\left(k\frac{p2\pi}{P}\right)+\sin(k2\pi f_c t)\sin\left(k\frac{p2\pi}{P}\right)\right] \\ &= P+\sum_{p=0}^{P-1}\sum_{j=1}^{n}c_jA+\sum_{j=1}^{n}\sum_{k=1}^{j}c_j\alpha_k\left[\cos(k2\pi f_c t)\sum_{p=0}^{P-1}\cos\left(k\frac{p2\pi}{P}\right)+\sin(k2\pi f_c t)\sum_{p=0}^{P-1}\sin\left(k\frac{p2\pi}{P}\right)\right] \end{aligned} \tag{11}$$

Since

$$\sum_{p=0}^{P-1}\sin\left(k\frac{p2\pi}{P}\right)=0 \text{ for all } k \tag{12}$$

and

$$\sum_{p=0}^{P-1}\cos\left(k\frac{p2\pi}{P}\right)=0 \text{ for } k \neq 0,\ P,\ 2P,\cdots \tag{13}$$

the expression for $w(t)$ in equation will reduce to the constant:

$$W(t)=P\left(1+A\sum_{j=1}^{n}c_j\right)a^n \tag{14}$$

if, and only if, the window order n is less than the number of planets P.

As the discrimination between planets increases with window order, the logical choice of window order is the highest we can achieve whilst keeping equation (11) constant for all t, ie an order of one less than the number of planet gears. Using this, the separated vibration signal estimate for planet p, equation (7) becomes:

$$v_p(t) = x(t)\beta_p(t) = x(t)a^{P-1}\left(1+\cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)^{P-1} \tag{15}$$

An estimate of the vibration during a single revolution of a planet p can be obtained by performing signal averaging of the separated vibration signal $v_p(t)$, equation (15) over N ensembles, each being one (relative) rotation of the planet gear as described in [1]:

$$\overline{v_p}(\tau) = \frac{1}{N}\sum_{n=0}^{N-1} v_p(\tau+nT) = \frac{a^{P-1}}{N}\sum_{n=0}^{N-1} x(\tau+nT)\left(1+\cos\left(2\pi f_c(\tau+nT) - \frac{p2\pi}{P}\right)\right)^{P-1} \tag{16}$$

where T is the time taken for one (relative) revolution of the planet gear. From equation (2) this is:

$$T = \frac{1}{f_p+f_c} = \frac{N_p}{f_c N_r} \tag{17}$$

and equation (16) becomes:

$$\overline{v_p}(\tau) = \frac{a^{P-1}}{N}\sum_{n=0}^{N-1} x\left(\tau+n\frac{N_p}{f_c N_r}\right)\left(1+\cos\left(2\pi f_c\tau + 2\pi n\frac{N_p}{N_r} - \frac{p2\pi}{P}\right)\right)^{P-1} \tag{18}$$

In the signal averaging process described in "A model for the extraction of periodic waveforms by time domain averaging" and "Interpolation techniques for the time domain averaging of vibration data with application to helicopter gearbox monitoring", the vibration signal $x(\tau+n\frac{N_p}{N_r})$ can be viewed as a composite of periodic vibration $\overline{x_p}(\tau)$ and non-periodic vibration $e(\tau+n\frac{N_p}{N_r})$ signals. Assuming that the summation of the non-periodic vibration signal tends toward zero, equation (18) can be estimated by:

$$\overline{v_p}(\tau) = \overline{x_p}(\tau)\frac{a^{P-1}}{N}\sum_{n=0}^{N-1}\left(1+\cos\left(2\pi f_c\tau + 2\pi n\frac{N_p}{N_r} - \frac{p2\pi}{P}\right)\right)^{P-1} \tag{19}$$

Applying equations (9) and (10), with window order of $P-1$, to equation (19) gives:

$$\overline{v_p}(\tau) = \overline{x_p}(\tau)a^{P-1}\left(C + \frac{1}{N}\sum_{j=1}^{P-1}\sum_{k=1}^{j} c_j\alpha_k\left[\cos(k\varphi)\sum_{n=0}^{N-1}\cos(k2\pi n\frac{Np}{Nr}) - \sin(k\varphi)\sum_{n=0}^{N-1}\sin(k2\pi n\frac{Np}{Nr})\right]\right) \tag{20}$$

$$where\ C = 1 + A\sum_{j=1}^{P-1} c_j\ \ and\ \ \varphi = 2\pi f_c\tau - \frac{p2\pi}{P}$$

In equation (20), if

(a) $\left(N\frac{N_p}{N_r}\right)$ is an integer and,

(b) $\left(k\frac{N_p}{N_r}\right)$ is not an integer, (21)

then $\sum_{n=0}^{N-1}\cos\left(k2\pi n\frac{N_p}{N_r}\right) = 0$ *and* $\sum_{n=0}^{N-1}\sin\left(k2\pi n\frac{N_p}{N_r}\right) = 0$, reducing (20) to:

$\overline{v_p}(\tau) = \overline{x_p}(\tau)Ca^{P-1}$

that is, for planet p, the separated signal average $\overline{v_p}(\tau)$ is a scaled version of the mean vibration signal $\overline{x_p}(\tau)$ if conditions (a) and (b) above are met. The scaling constant c can be easily calculated and, in practice, the signal averages can be divided by this constant giving the unscaled mean vibration signal.

The condition that $(N\frac{N_p}{N_r})$ is an integer is easily met by setting the number of averages N to be an integer multiple of the number of teeth on the ring gear N_r. The second condition, that $(k\frac{N_p}{N_r})$ is not an integer, is a function of the number of teeth on the planet gears, N_p, the number of teeth on the ring gear, N_r and the order of the window (in this case $P-1$ = number of planet gears - 1). In practice, it is highly unlikely that the ratio $(\frac{N_p}{N_r})$ for any epicyclic gear is such that, when multiplied by an integer between 1 and P-1, an integer results; if this was the case, the order of the separating window should be reduced to a value n such that $(k\frac{N_p}{N_r})$ is not an integer for any integer k between 1 and n.

In the above theoretical development of the technique, it is assumed that the speed of the epicyclic gearbox is constant. In practice, even for a nominally constant speed machine, this is not always the case. To allow for speed fluctuations all analysis is done in an 'angular' domain rather than a time domain; this simply involves the substitution of an angular reference for the time based variable t in the above theoretical development.

The conversion from the time domain to the angular domain may be done by synchronising the vibration signal sampling with an angular reference on one of the shafts of the gearbox. The synchronisation can be done either using phase-locked frequency multipliers or by digital resampling (ie sampling the data plus a angular reference at fixed time intervals and then resampling at the required angular positions by interpolation).

The procedure used for implementing the planet separation technique described is given schematically in Figure 2. Here the functions B1(R) etc. represent the angular domain versions (relative to planet carrier position R) of the separation functions $\beta_p(t)$, defined in equation (6). This can be implemented either in hardware, software or a combination of the two. After the vibration signal is passed through the p separation functions, the individual planet signal averages are calculated in exactly the same fashion

as for conventional signal averaging as long as the number of averages is an integer multiple of the number of teeth on the ring gear (as detailed above).

In Figure 2, a planet carrier positional reference (R) is required for the calculation of the planet separation windows. This can be obtained either by using a shaft encoder/tacho on the planet carrier (usually the output of the gearbox) or by software synchronisation to the planet pass modulation signal. If a shaft encoder/tacho is used, the relative positions of the planet gears, transducer and shaft position reference needs to be known to determine the planet separation functions – a zero position for R would be set at which point a particular planet (p=0 in equation (6a)) is adjacent to the transducer location.

In the case where a carrier positional reference is not directly available, the planet carrier position can be estimated by examining the 'planet pass modulation'. This involves performing a signal average of planet carrier (ring gear) vibration. As each planet passes the transducer location the vibration level increases, giving an amplitude modulation of the vibration signal. Demodulation of the ring gear signal average about the gear mesh vibration [5] is used to determine the modulation peaks as each planet gear passes the transducer location. Figure 3 shows the results obtained from demodulation for a epicyclic gearbox with three planet gears. Here the peaks as each planet passes the transducer location can be clearly seen. The point with the maximum amplitude in the demodulated signal average is selected as the zero position for the planet carrier position reference (R); this can be done either during post processing of a stored vibration signal (in which case the same stored signal is used for planet separation) or during real time processing as a prelude to planet separation (in which case tracking of the planet carrier rotation must continue in parallel with the calculation in order to commence planet separation at the appropriate point on a subsequent revolution of the planet carrier).

Enhancement techniques:

Any of the enhancement techniques currently applied to coherently averaged vibration data for the purpose of fault detection can be applied without modification to the separated planet gear signal averages provided by the current invention.

Narrow Band Envelope:

In the following examples, the 'kurtosis' of the 'narrow band envelope' enhancement of the separated planet gear signal averages is used as an indicator of tooth damage. The narrow band envelope enhancement [5] involves the removal of all frequencies in the signal average except for those in a narrow band centred about one of the dominant tooth mesh harmonics. The centre frequency is also removed and the time domain envelope (amplitude of the complex time representation of the signal) is then calculated. This 'narrow band envelope' is a function of the amplitude and phase modulation of the centre frequency (tooth mesh harmonic) as represented by the components in the band chosen. That is, it is representative of the deviation from a pure sine wave at the selected centre frequency and is used as a measure of the variation in the meshing behaviour of individual teeth with respect to the mean meshing behaviour of all the teeth on the gear.

The 'kurtosis' (defined below) of this signal is used as a measure of tooth damage.

Kurtosis:

'Kurtosis' is defined as the fourth statistical moment of a signal about its mean. The kurtosis can be normalised by dividing by the fourth power of the standard deviation of a signal, providing a non-dimensional measure of isolated peaks in the signal. In the following examples 'kurtosis' is used to mean 'normalised kurtosis' defined (for a discrete signal) as:

$$K = \frac{N\sum_{i=1}^{N}(x_i-\bar{x})^4}{\left[\sum_{i=1}^{N}(x_i-\bar{x})^2\right]^2}$$

where: K = normalised kurtosis and

$\bar{x}$ = mean value of signal

The normalised kurtosis for a sine wave is 1.5 and for Gaussian noise it is 3.0. Isolated peaks in a signal will give 'kurtosis' values > 3.0. In gear fault detection, the normalised kurtosis is useful in detecting isolated peaks caused when the meshing behaviour of one gear tooth is statistically different from the mean meshing behaviour of all the teeth on the gear. As a general rule of thumb, a 'kurtosis' value >3.5 indicates a statistically significant localised change (used here as a 'warning' of a tooth fault) and >4.5 indicates a very significant localised change (used here as a 'danger' indication).

In the following examples, a software implementation of the planet separation technique has been used. This was performed on a PC with an Intel 80486 processor, Data Translation DT-2821-G analogue-to-digital converter and an Online TechFilter anti-aliasing filter.

Figure 4 shows results of the test which was performed on a simulated signal consisting of eight identical amplitude modulated sine waves:

$$s(t)=\frac{1}{2}(1+\cos(2\pi t))\cos(2\pi t\times 130)$$

which were combined by time shifting:

$$x(t)=\sum_{p=0}^{7} s\left(t-\frac{p}{8}\right)$$

The combined signal represents a simplistic model of the fundamental tooth mesh vibration from the lower stage epicyclic of a Eurocopter Super Puma Mark I helicopter main rotor gearbox, which has eight planet gears each having 34 teeth, a ring gear with 130 teeth and a sun gear with 62 teeth. In the above, the time variable t represents the time taken for one revolution of the planet carrier. That is, t=1 represents the time taken for one complete revolution of the planet carrier, t=34/130 represents the time taken for one revolution of a planet gear and t=62/130 represents the time taken for one revolution of the sun gear.

A first order amplitude modulation function has been used here. This gives individual signals with a maximum amplitude of 1, a minimum amplitude of 0 and a mean amplitude of 0.5. Higher order modulation functions would give the same maximum and minimum amplitudes but a different mean amplitude.

Planet separation was performed on the simulated signal using the new invention previously described (with a window order of 7 and division by the constant window integral to remove scaling effects) and the snapshot technique described in [1] and [2]. Figure 4 shows the signal average and its spectrum for one of the separated signals using (a) the new technique and (b) the snapshot technique. The two techniques were applied over the same data (t=0 to 10). The new technique, Figure 4(a), correctly extracts the pure sine wave (34 orders of the planet rotation as seen in the signal average spectrum) with a constant amplitude of 0.5 (RMS of 0.35), being the mean amplitude of the original signal. Note that a seventh order window was used for the separation and the actual modulation was only a first order function; indicating that the relationship between these has no influence on the effectiveness of the method. Even in this very simple model the snapshot technique, Figure 4(b), introduces discontinuities into the separated signal average. These can be seen as small components at 17 and 51 orders in the signal average spectrum in 4(b). The signal extracted by the snapshot technique has a mean amplitude of 1 (RMS of 0.7), being the maximum amplitude of the original signal.

The software performed the planet separation by post-processing of digitised vibration and tacho signals.

The following example was from a recorded vibration signal of an epicyclic gearbox with three planet gears each having 32 teeth, a sun gear with 28 teeth and a ring gear having 95 teeth. A small fault was implanted on one tooth on one of the planet gears [1]. McFadden and Howard [1] suggested they were able to detect this fault with the snapshot technique using 32 averages. This represents approximately 240 seconds (4 minutes) of run time; a similar number of averages for the epicyclic on the Sea King helicopter would require over nine minutes.

For this example, the analysis time has been reduced to 75 seconds (10 x 32 revolutions of the planet carrier).

Figure 5 shows the results obtained by performing a narrow band envelope enhancement [5] on the separated signal averages for the faulty planet using (a) the new separation technique and (b) the snapshot technique. A 'composite' signal average is also shown (c) for comparison (the 'composite' average is simply the result of performing regular signal averaging [3,4,5] at the planet rotational speed without trying to separate the individual planets). The 'kurtosis' of the narrow band envelopes is used as a measure of local variation in the tooth meshing behaviour. A kurtosis value greater than 4.5 is considered to be a clear indication of a local defect and a value below 3.5 indicates a 'good' gear.

The new technique gives a kurtosis of 7.2, clearly indicating the presence of the fault. Over the same analysis period, neither the snapshot technique (kurtosis=2.4) nor the composite averaging (kurtosis=2.8) give any indication of the fault.

Figure 6 shows the comparative performance of (a) the McFadden & Howard 'snapshot' technique and (b) the new planet separation technique over varying lengths of data for the planet gear fault test described above. The graphs show the 'kurtosis' of all three planet gears ('Gear2' is the damaged planet gear, 'Gear1' and 'Gear3' are undamaged) versus the number of 'averages' used for the analysis; the graphs also include the warning (kurtosis=3.5) and danger (kurtosis=4.5) levels for reference. Each 'average' represents 32 revolutions of the planet carrier which, in this case, is approximately 7.5 seconds of data. Identical data has been used for both methods.

As can been seen, the difference in performance of the two methods is striking. The 'snapshot' technique, Figure 6(a) behaves in an erratic fashion: only giving a clear indication of a fault on gear 2 after 20 'averages' and with poor separation of the planets (ie a false fault indication is seen on gear 3). In direct contrast to this erratic behaviour, the new planet separation technique, as seen in Figure 6(b), shows a remarkably efficiency and stability. After only 1 'average', a very clear fault indication is given on

gear 2 with relatively good separation (gear 3 just above warning level). After only 3 'averages' excellent fault detection and planet separation has been achieved (no evidence of fault in the undamaged gears). After 10 'averages', the new planet separation technique has stabilised and very little change occurs with further averaging.

In the description of the invention given, it was mentioned that there are preferably constraints on the nature of the filter functions β_p.

More generally, the filter functions β_p should usually substantially satisfy the following:

(*a*) $\sum_{p=0}^{P-1} \beta_p(\phi) =$ constant for all ϕ and,

(*b*) $\sum_{n=0}^{N-1} \beta_p(\phi + n2\pi \frac{N_p}{N_r}) =$ constant for all ϕ

where ϕ is the angular position of the planet carrier;

N_p is the number of teeth on the planet gears;

N_r is the number of teeth on the ring gears; and

N is the number of rotations of the planet gear(s) over which the signal averaging is performed.

The required "separation" function achieved by the filter functions β_p may be viewed as being provided by amplitude variation in $\beta_p(\phi)$. It should be noted that $\beta_p(\phi) = 1$ or $= 0$ (no signal at all) meets these conditions but will not in general provide separation of components due to the individual planetary gears.

In another aspect the invention provides a method of performing selective signal averaging on epicyclic gearboxes comprising filtering a vibration signal arising from use of the gear box by application of a filter function which models the variation of the vibration signal which would occur if only one planet gear of the gearbox were present

In yet another aspect the invention provides a method comprising filtering a

vibration signal arising from use of a gear box by application of a filter function which models the variation of the vibration signal which would occur if respective ones of the planet gears of the gearbox were present.

The vibration signal may be represented by a mathematical function of time or angular displacement.

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2. Howard, I.M., "An investigation of vibration signal averaging of individual components in an epicyclic gearbox". Department of Defence, Aeronautical Research Laboratory, Propulsion Report 185, March 1991.

3. McFadden, P.D., "A model for the extraction of periodic waveforms by time domain averaging", Department of Defence, Aeronautical Research Laboratory, Aero Propulsion Technical Memorandum 435, March 1986.

4. McFadden, P.D., "Interpolation techniques for the time domain averaging of vibration data with application to helicopter gearbox monitoring", Department of Defence, Aeronautical Research Laboratory, Aero Propulsion Technical Memorandum 437, September 1986.

5. McFadden, P.D., "Examination of a technique for the early detection of failure in gears by signal processing of the time domain average of the meshing vibration", Mechanical Systems and Signal Processing, Vol. 1(2), 1987, pp. 173-183.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for estimating the contribution, due to individual ones of a plurality of planet gears in an epicyclic gearbox having a ring gear, in a vibration signal generated by sensing vibration of a ring gear of the gearbox at a location on the ring gear during operation of the gearbox, comprising filtering the vibration signal by application of filter functions which models the time variation of the vibration signal at said location which would occur if only respective ones of said planet gear were present, said functions, for individual planet gear and, being of form:

$$\beta_p(t) = \left(a\left(1 + \cos\left(2\pi f_c t - \frac{p2\pi}{P}\right)\right)\right)^n$$

where f_c is the frequency of rotation of the planet carrier;
a and n are constants;
P is the number of planet gears; and
t is time,
or said filter function being of form

$$\beta_p(\phi) = \left(a\left(1 + \cos\left(\phi - \frac{p2\pi}{P}\right)\right)\right)^n$$

where ϕ is the angular position of the planet carrier;
P identifies the individual planet gear;
a and n are constants; and
P is the number of planet gears;

wherein the filter functions β_p satisfy the following:

(*a*) $$\sum_{p=0}^{P-1} \beta_p(\phi) = \text{constant for all } \phi \text{ and,}$$

(*b*) $$\sum_{k=0}^{N-1} \beta_p\left(\phi + k2\pi\frac{N_p}{N_r}\right) = \text{constant for all } \phi$$

where ϕ is the angular position of the planet carrier;

N_p is the number of teeth on the planet gears;

N_r is the number of teeth on the ring gears; and

N is the number of rotations of the planet gear over which the signal averaging is performed; and

said constant n is in the range 0 to P−1; and

the filtered signal is averaged to produce measures of said contributions.

DATED this 1st day of August, 1996

COMMONWEALTH OF AUSTRALIA
By its Patent Attorneys
Davies Collison Cave

ABSTRACT

A method for estimating the contribution, due to one of a plurality of planet gears in an epicyclic gearbox having a ring gear, in a vibration signal generated by sensing vibration of a ring gear of the gearbox during operation of the gearbox, comprising filtering the vibration signal by application of a filter function which models the time variation of the vibration signal at said location which would occur if only said one planet gear were present.

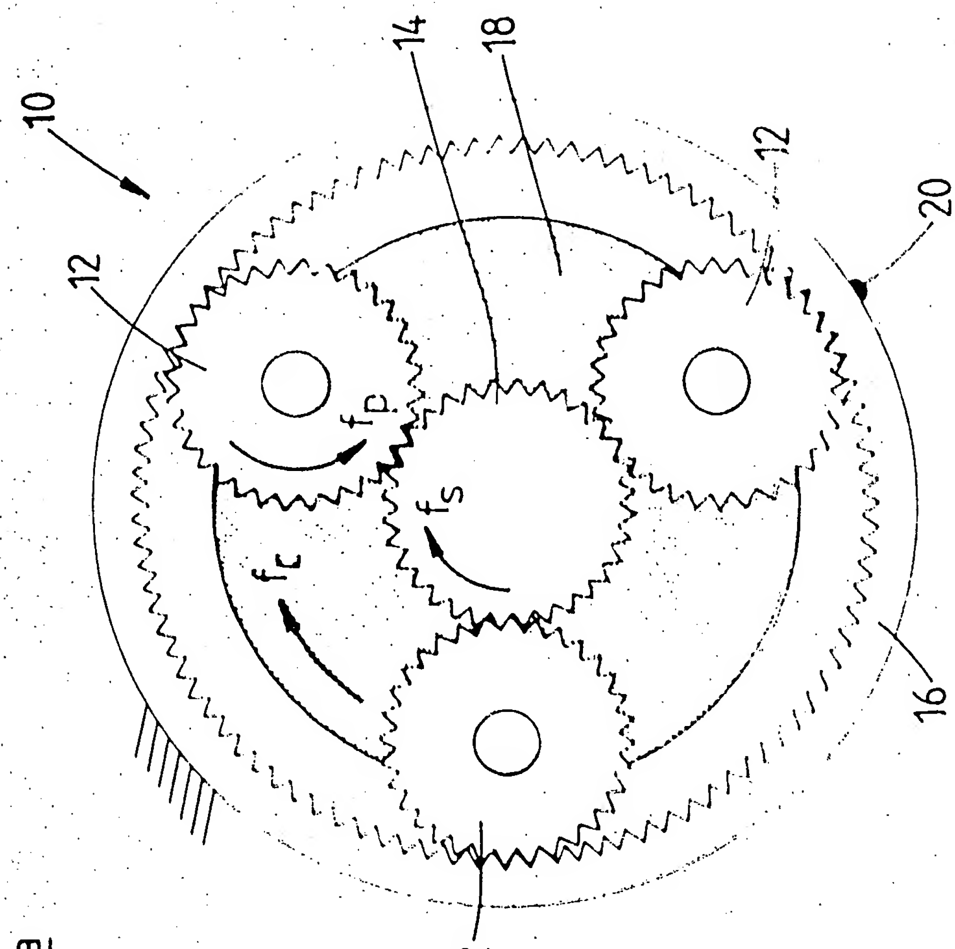
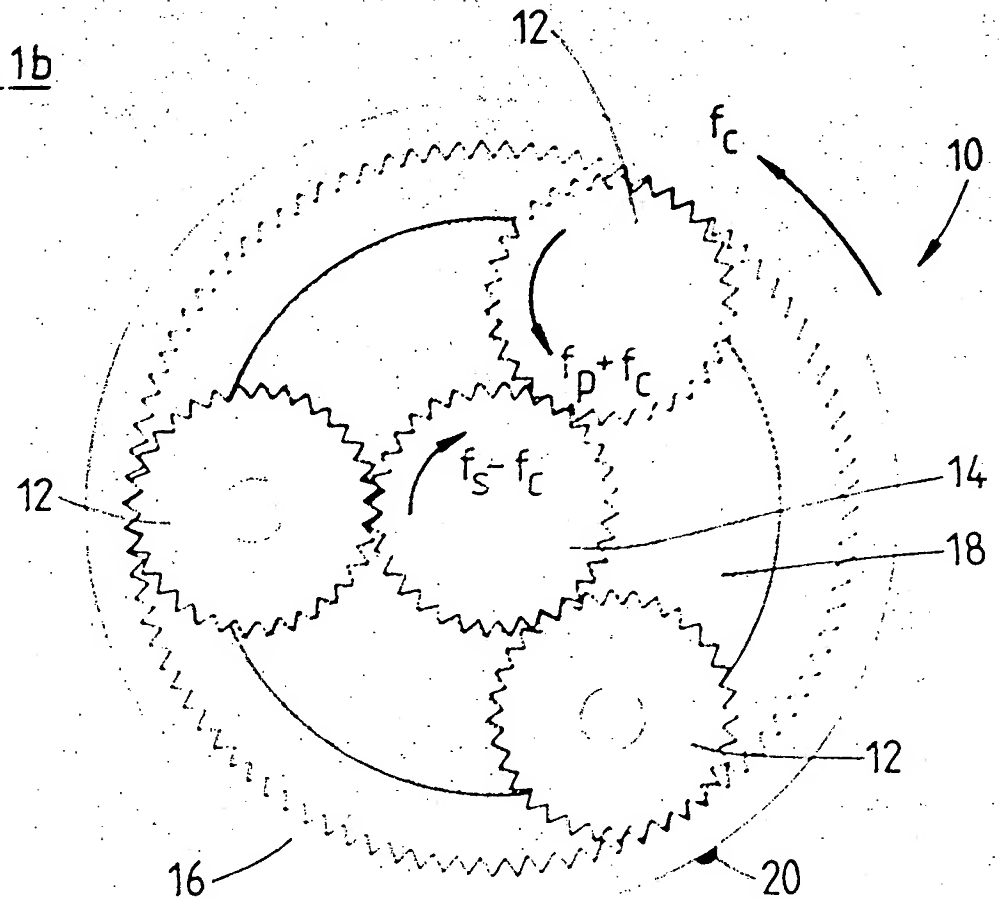


FIG 1a

FIG 1b



40638/95

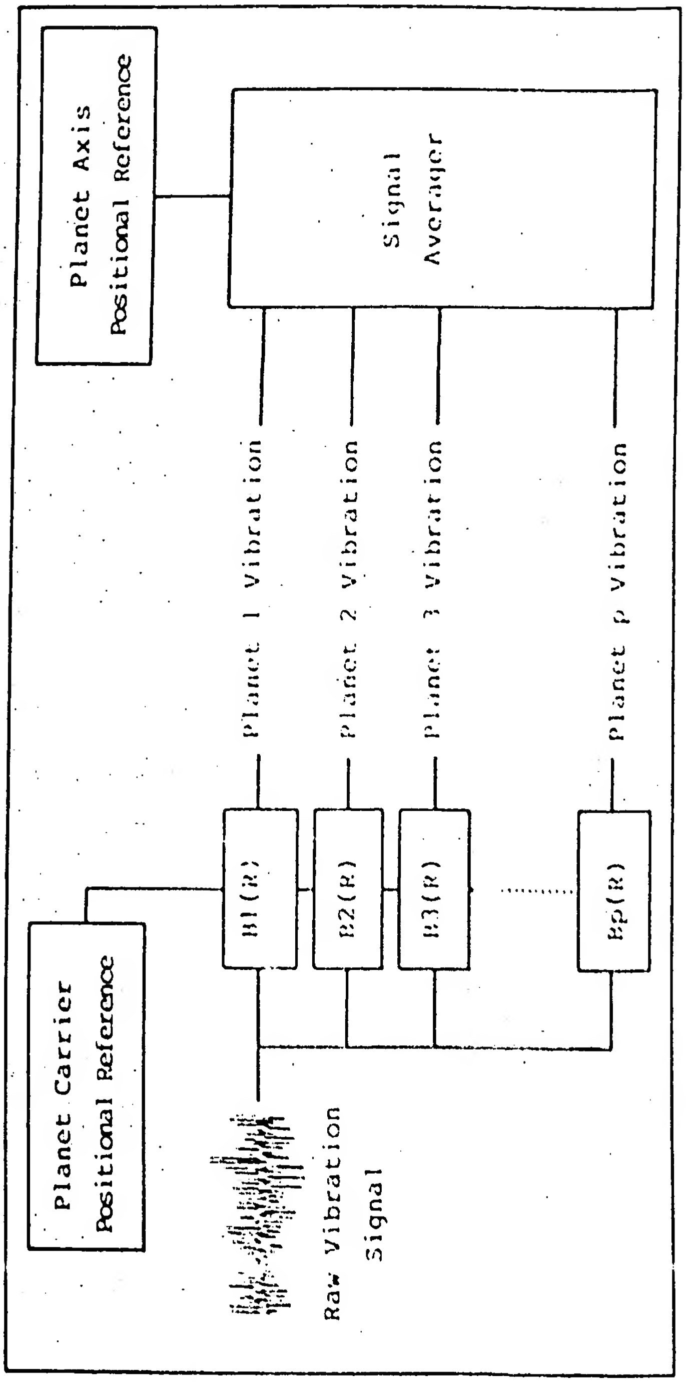


FIGURE 2

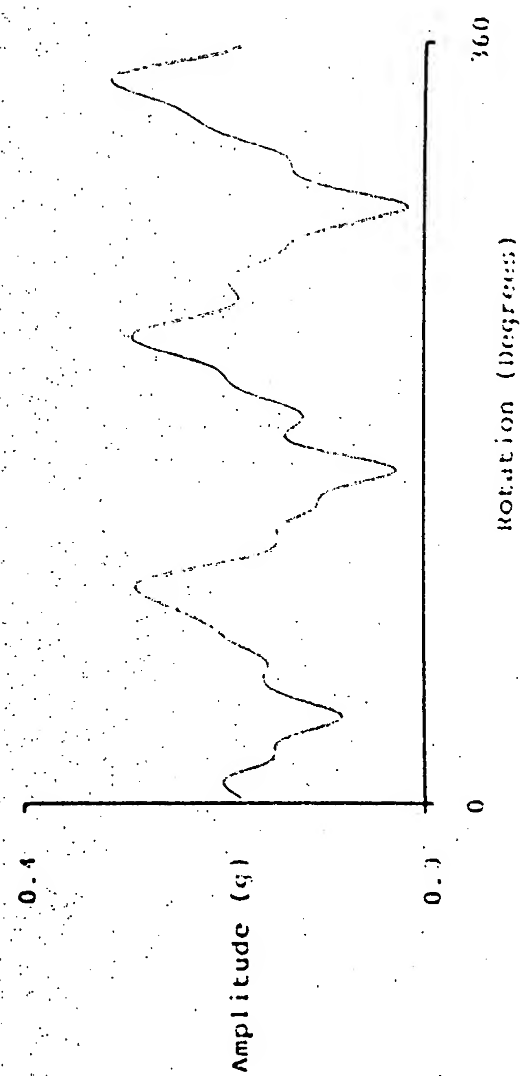


FIGURE 3

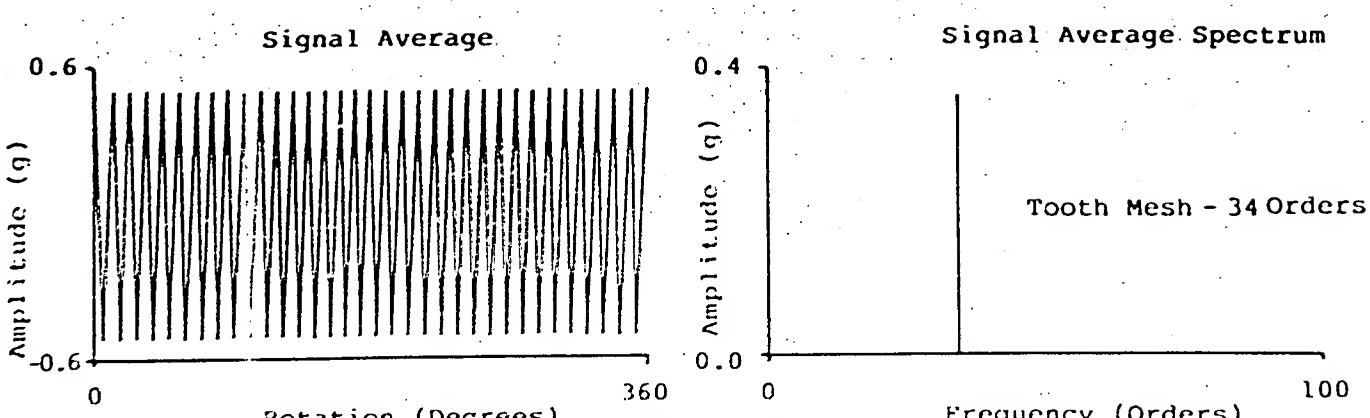


FIGURE 4a

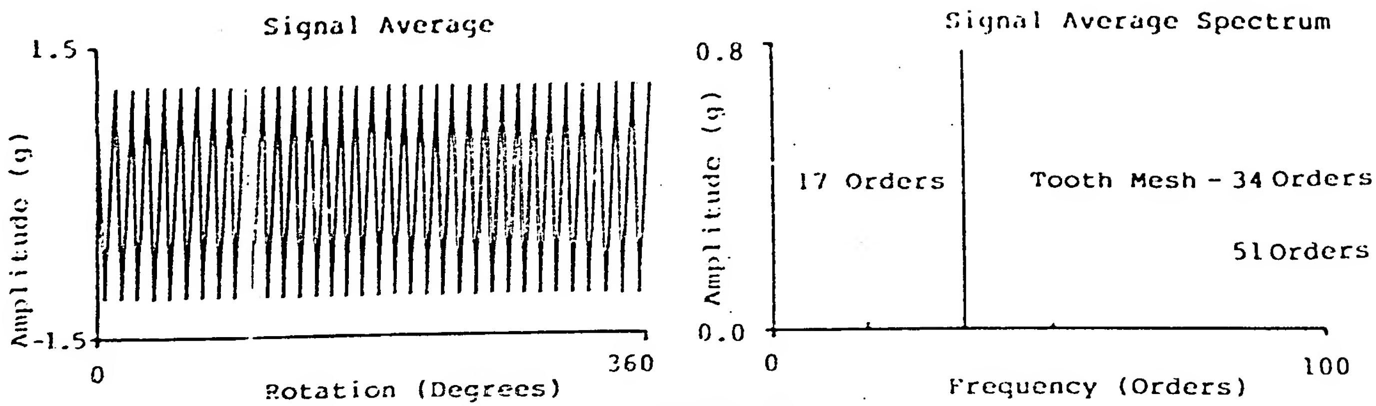


FIGURE 4b

FIGURE 5a

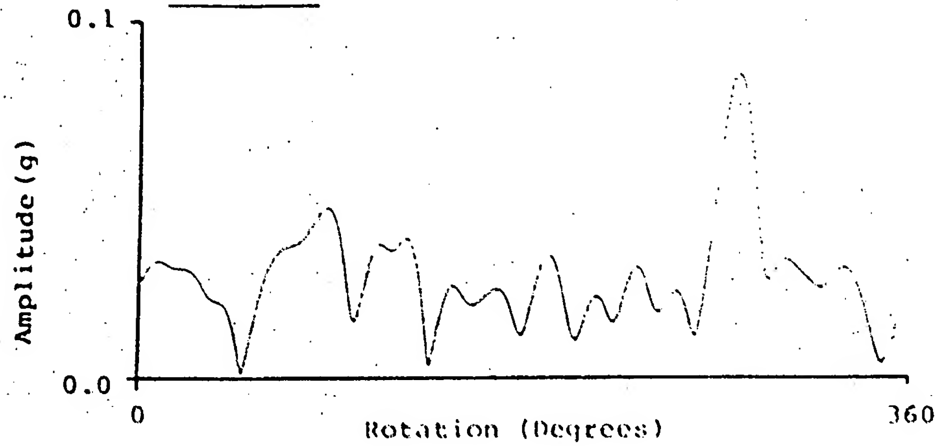


FIGURE 5b

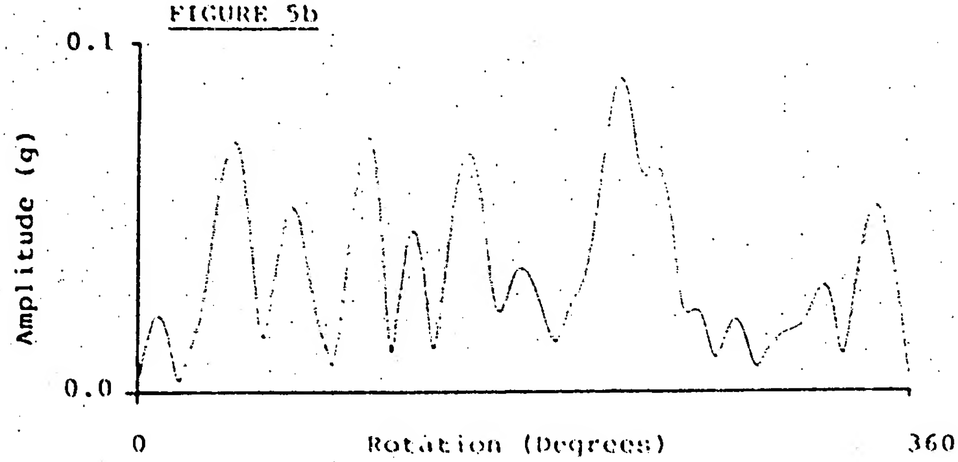
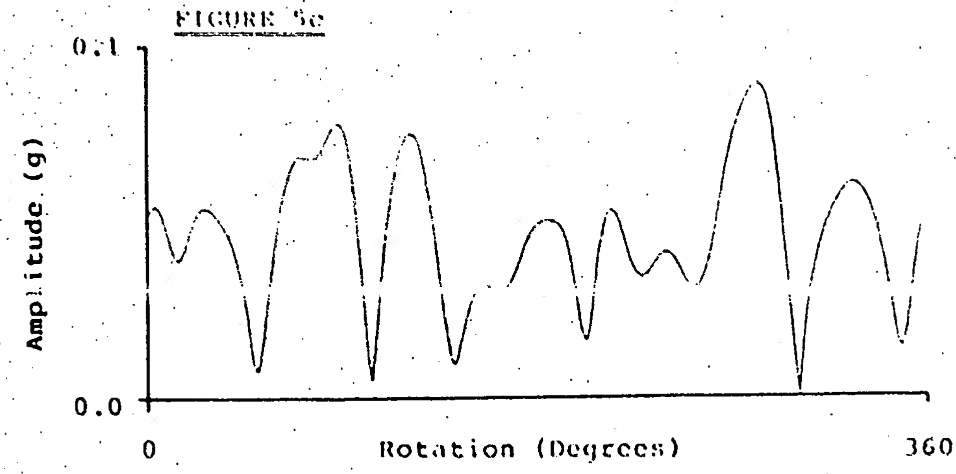


FIGURE 5c



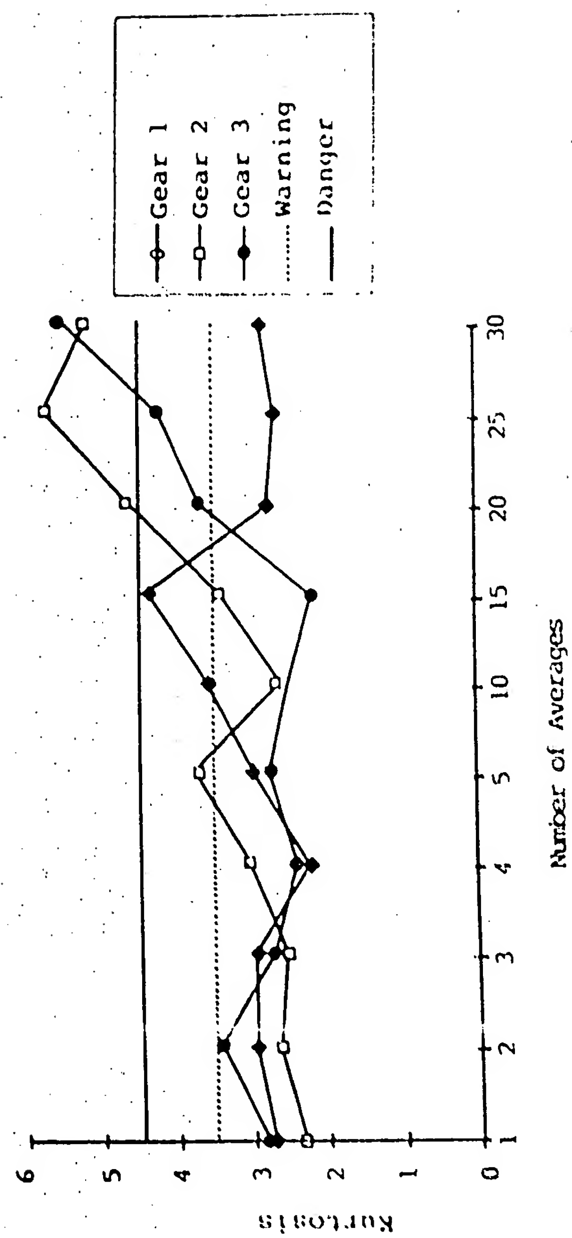

Kurtosis
0
1
2
3
4
5
6
Number of Averages
1
2
3
4
5
10
15
20
25
30
Gear 1
Gear 2
Gear 3
Warning
Danger

FIGURE 6:

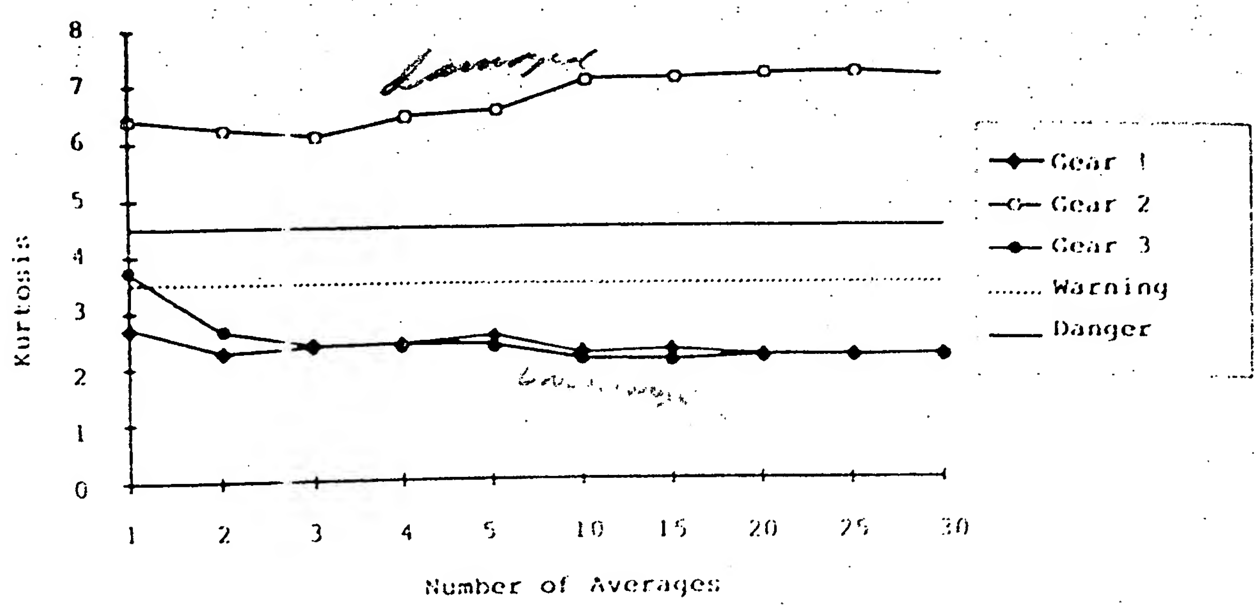

Kurtosis
0
1
2
3
4
5
6
7
8
1
2
3
4
5
10
15
20
25
30
Number of Averages
Gear 1
Gear 2
Gear 3
Warning
Danger

FIGURE 6b